“Early Galaxies, Stars, Metals, and the Epoch of Reionization”

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Submillimeter Galaxies: only the brightest?
How long? [dust forming? de-shrouding]
Some “Big Picture” Questions

(1) When and how did the first galaxies form?
   - Was the IMF different? ($M_{\text{max}}$, $M_{\text{min}}$, slope)
   - Where did the first metals & dust come from?
   - Which galaxies reionized the IGM?
   - Star-formation, ionization efficiency?
   - Primordial coolants? ($H_2$, metals, dust)

(2) How did later stars/galaxies assemble?
   - Mergers, cold accretion, rise of metallicity
   - Black Hole Co-Evolution and “deshrouding”
   - Duration of rapid-accretion, dusty phase?
This optical depth can be produced by a fully ionized IGM (at $z \leq z_{rei} \approx 7$)

$$\Rightarrow \tau_e = 0.05$$

Plus additional optical depth

$$\Delta \tau_e \approx 0.03 \text{ at } z > 7$$
CMB Opt Depth: $\tau_e \approx (0.05)[(1+z_r)/8]^{3/2}$

ioniz by stars/AGN ($z \leq 7$)

Barkana 2003

Shull & Venkatesan 2008
Evolution of Low-Metal Stars

Why important?

Increased $T_{\text{eff}}$ for Pop III stars at low metallicity

10-100 $M_{\odot}$ dominate the IGM ionization

but for how long?

$10^7$ to $10^8$ yrs
When is the transition (Zero-metal to Pop II stars?)


140-260 M$_{\text{sun}}$ Pair Instability Supernovae

Produce 50-100 M$_{\text{sun}}$ of heavy elements (O, Si, Fe)

Zero-Metal Peak ~100 M$_{\text{sun}}$
Cosmology: Halo Mass Distribution and Baryon fraction

\[ f_b(z) = \text{baryon fraction in halos} \]
\[ f^*(z) = \text{fraction of stars formed} \]

"efficiency of ionization"

\[
(Ioniz\ Frac) = \frac{f_b(z) \left[ f^*(z) N_Y f_{esc}(z) \right]}{(clumping)}
\]

Star formation and stellar astrophysics

Interstellar physics and radiative transfer
Ionization Efficiency = $[f^* N_\gamma f_{\text{esc}}]$ 
(type of halos and stars needed at $z_r > 7$)

Extra CMB optical depth (at $z > z_r$)

Shull & Venkatesan 2008

Pop III mini-halos, stars transition to Pop II
High-Redshift Star Formation ($z = 12.5$) -- “Cosmic Web”

$H_2$ cooling

$z = 12.5$
What might the First Stars look like?

Slow cooling and gravitational collapse of proto-galactic clouds (Abel 2007)
Molecular Hydrogen in the Dark Ages


$0.005 < Z < 0.05 \, Z_{\text{sun}}$

$X_{\text{H}_2} \approx 10^{-4}$

$T \approx 5000 \, \text{K}$
Early Star Formation (Mini-halos)

DM Halos:

$$f^* = 0.05$$

$$5 \times 10^7 \, M_{\text{sun}}$$
Star-Formation Rates

\[ \text{SFR} \approx 0.05 \, M_{\text{sun}}/\text{yr} \]

\[ M^* \approx 5 \times 10^6 \, M_{\text{sun}} \]

\[ M_{\text{DM}} \approx 10^8 \, M_{\text{sun}} \]
Predictions for JWST (K-band)

[dwarf primordial galaxies at z > 8]

NIRCAM detection limit (10^5 sec)

100 nJy sources 10 per field
Growth rate of IGM metallicity (for SFR density over 1 Gyr)

\[
\frac{\dot{Z}}{Z_\odot} = \frac{\rho(SFR)y_m t}{\Omega_b h^2 \rho_c(0.02)} = \frac{(0.1 \ M_\odot \ yr^{-1} \ Mpc^{-3})(0.024)(10^9 \ yr)t_9}{(0.0224)(1.879 \times 10^{-29} \ g \ cm^{-3})(0.02)} = (0.019) \left[ \frac{\rho(SFR)}{0.1 \ M_\odot \ yr^{-1} \ Mpc^{-3}} \right] t_9.
\]

Z\rightarrow 1\% \ solar \ in \ \sim \ Gyr

Assumed metal yield \( y_m = 0.024 \) (per \( M_{\odot} \))

SFR density scaled to peak value (\( z = 2-6 \))

\[
SFR \approx 0.1 \ M_{\odot} \ yr^{-1} \ Mpc^{-3}
\]
The first stars, galaxies, and quasars enrich the surrounding gas

High-mass stars make O, Si, Fe (and some C)
They are prodigious LyC emitters (reionization)

What happens next?

• When does gas cooling exceed adiabatic heating?
• At what $Z_{\text{crit}}$ does F-S cooling exceed $\text{H}_2$ cooling?
• Transition from (zero-metal) to Pop II stars?
• Dependence on stellar mass range (O, Si, Fe)?
• Time-dependent cooling, coupling to CMB?
Duration of Metal-Free Phase?
(Self-polluting $10^6 \, M_{\odot}$ halos at $z = 10-20$)

t $\approx 10^7$ to $10^8$ yr

- $R_{\text{vir}} = (160 \, \text{pc}) \, M_6^{1/3} \left[ \frac{20}{(1+z)} \right]$
- $T_{\text{vir}} = (1060 \, \text{K}) \, M_6^{2/3} \left[ \frac{(1+z)/20}{20} \right]$
- $n_{\text{vir, H}} = (0.27 \, \text{cm}^{-3}) \left[ \frac{(1+z)/20}{3} \right]^3$

The rest of metals blow out into the IGM
Molecular Cooling (H$_2$ rotational lines)

Strongest transitions are from ortho-H$_2$ (J = 3-1) and from para (J = 2-0) rotational states, excited in neutral clouds primarily by H$^0$ - H$_2$ collisions.

Strongest transitions have critical densities

\[ n_{cr} \approx 10^3 \text{ to } 10^4 \text{ cm}^{-3} \]

- J = 2 $\rightarrow$ 0 (28.22 microns)  \( T_{exc} = 510 \text{ K} \)
- J = 3 $\rightarrow$ 1 (17.03 microns)  \( T_{exc} = 1015 \text{ K} \)

Santoro & Shull (2006, 2008)
Abundant Heavy Elements
(with ground-state fine structure lines*)

No fine structure in S II, Mg II, Ca II, Ar I

- C II (2p) $^2P_{1/2,3/2}$ 157.74 microns
- O I (2p$^4$) $^3P_{2,1,0}$ 63.18 & 145.5 microns
- Si II (3p) $^2P_{1/2,3/2}$ 34.8 microns
- Fe II (4s 3d$^6$) $^6D_{9/2,7/2}$ 25.99 microns

*Assume ionization state set by FUV photons (E < 13.6 eV)

Thus, dominant ions are C II, Si II, Fe II
Locus of Minimum $Z_{\text{crit}}$ values

High-mass stars: nucleosynthetic products (O, Si, Fe)

1% Solar

LTE
Time-dependent Cooling

\[ z_i = 30 \]

Cooling to \( n = 10^4 \text{ cm}^{-3} \) requires \( Z_{\text{crit}} \approx 10^{-2} Z_{\text{sun}} \) at \( n = 100 \text{ cm}^{-3} \)

\[ T_{\text{CMB}} \approx 80 \text{ K} \]

\[ [\text{Fe/H}] = -4.0 \]

Inflection Pt

\[ \text{Temperature} \]

\[ \log(T/\text{K}) \]

\[ \log(n/\text{cm}^{-3}) \]
\[ \log_{10}(M_{\text{Jean}}/M_\odot) \]

\[ \log_{10}(n/\text{cm}^{-3}) \]

-2.0
-2.4
-3.0

[Fe/H] = -4.0

[Fe/H] = -1.0

100 \( M_\text{sun} \)

10 \( M_\text{sun} \)

LTE
Fine-Structure Line Luminosities (LTE)
($10^8 \, M_{\text{sun}}$ cooling at 200 K and 0.01 $Z_{\text{sun}}$)

Strongest lines:
- Fe II 26 μm, O I 63 μm,
- Si II 35 μm

[O I] 63 μm redshifted into the FIR/sub-mm (e.g., 350 μm window)

$L_i = 10^{41-42}$ erg/s

Fluxes (z=4)
- $10^{-21}$ to $10^{-20}$ W m$^{-2}$
H$_2$ emission will be much stronger in merging systems.

More gas (10$^9$-10 $M_{\text{sun}}$) and hotter (shocks).
Astrophysical Summary

• Primordial Dwarf galaxies ($10^6$-$7$ $M_{\text{sun}}$) - 100 nJy sources (K-band)
• Reionization ($z \approx 8$-$10$) by early massive stars and BHs (X-rays)
• High-z: individual values of $Z$(C, O, Si, Fe) - enhanced O,Si,Fe)
• Primordial cooling $H_2$ and FS lines: FIR at $10^{-21}$ to $10^{-20}$ W m$^{-2}$
  (easier to detect $H_2$ in shocked/merging systems)

These observations will require major (large) telescopes